Professor M.R. Jolly, PhD, BMet, Professor of Sustainable Manufacturing
Dr. K. Salonitis, PhD, MBA, Dip. Eng., Senior Lecturer in Manufacturing Systems
Cranfield University, Cranfield, United Kingdom, MK43 0AL

Primary Manufacturing, Engine Production and on-the-road CO_2: How can the Automotive Industry Best Contribute to Environmental Sustainability?

Rohstoffverarbeitung, Motorenfertigung und CO_2-Ausstoß auf der Straße: Wie kann die Automobilindustrie bestmöglich zu ökologischer Nachhaltigkeit beitragen?

Abstract

Legislation in the automotive industry currently focusses on tailpipe CO_2 emissions, with no consideration for the CO_2 footprint of the materials used in the manufacture of vehicles. This has led OEMs to adopt lower density materials, to contribute to weight reduction and fuel economy, in the expectation that the weight reduction will provide a net CO_2 benefit to society.

This paper will present the results of a full assessment of the energy and CO_2 impact during the manufacture of diesel and petrol engine blocks. The research is based on inputs from over 100 world experts from across the automotive supply chain, including raw material mining and smelting companies, alloy recyclers, iron and aluminium foundries, OEM engineers, independent manufacturing specialists, design consultants, heat treaters and impregnators. Despite current perceived wisdom, the use of lower density materials frequently results in net energy and CO_2 penalties, when considering the complete life cycle of manufacture and use. For the 1.6 litre engine block investigated in this study, more than 200,000 km of on-the-road driving is required to compensate for the up-front energy consumption and CO_2 emissions associated with the production of aluminium engine blocks. The paper also comments on other environmental impacts from the iron and aluminium manufacturing routes. These results provide new insights for OEM decision-makers, and a new perspective for legislators to define regulations that truly contribute to the environment and to society.

Kurzfassung

Die gesetzlichen Vorgaben der Automobilindustrie konzentrieren sich bei den CO_2 Abgasemissionen nur auf den Fahrzeugbetrieb. Den Energiebedarf sowie die entstandenen CO_2 Emissionen der eingesetzten Materialen, die zur Herstellung der Fahrzeuge entstehen finden bei dieser Betrachtungsweise jedoch keine Berücksichtigung. Dieser Umstand hat dazu geführt, dass OEM´s Materialien mit geringer Dichte nutzen, um so eine Gewichts- und Verbrauchsreduzierung zu erzielen. In der Annahme, dass die Gewichtsreduzierung mit einer gleichzeitigen CO_2 Reduzierung einher geht.

Diese Studie stellt die Ergebnisse einer sehr umfangreichen Energie- und CO^2 Bilanz für den Herstellprozess von Diesel- und Benzinzylinderkurbelgehäusen vor. Die Studie basiert auf Eingaben von über 100 führenden Experten aus der Automobilzulieferindustrie inkl. Bergbau, Hüttenbetriebe, Recyclingbetrieben, Eisen- und Aluminiumgießereien, OEM Entwicklern, unabhängigen Fertigungsspezialisten, Entwicklungsberatern, Wärmebehandlungs- und Imprägnierungsbetrieben.

Ungeachtet der allgemeinen / gegenwärtigen Wahrnehmung, führt die Verwendung von Materialien mit geringerer Dichte, bezogen auf den gesamten Lebenszyklus (cradle to grave), in der Regel zu einem erhöhten Energiebedarf und CO_2-Ausstoss.

Bei dem dieser Studie zugrundegelegten 1.6 Liter Aluminium Zylinderkurbelgehäuse ist eine Kompensation der zur Herstellung eingesetzten Energie und der CO_2 Emissionen erst nach mehr als 200,000 km gegeben. Die Abhandlung bezieht sich ebenfalls auf weitere Umweltauswirkungen der Eisen-/Aluminium- Herstellungsmethoden. Diese Studienergebnisse bieten OEM Entscheidungsträgern sowie den Gesetzgebern neue Erkenntnisse, um gesetzliche Vorschriften zu definieren, die einen reellen Beitrag zum Umweltschutz leisten.

Introduction

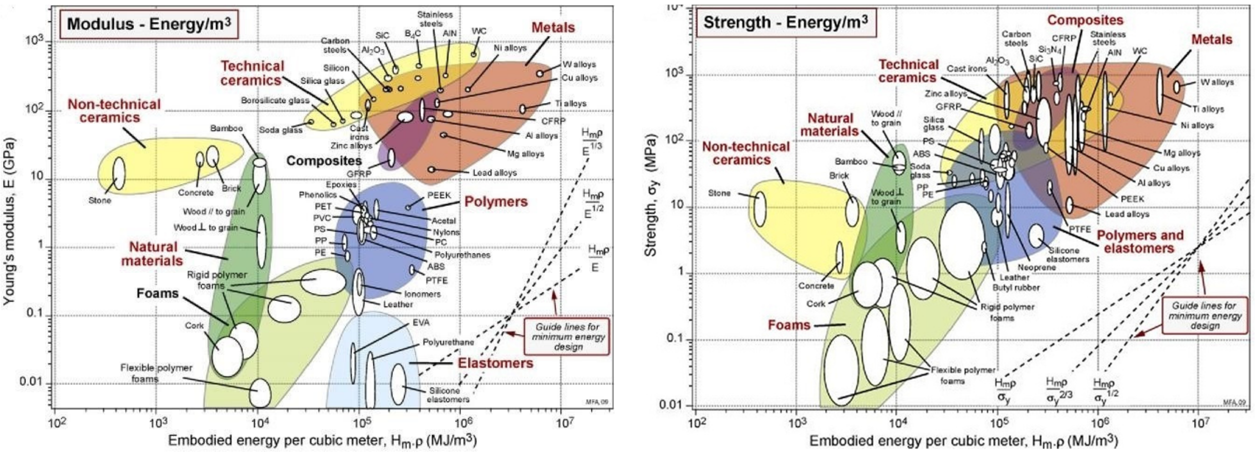
This paper is a result of research carried out by talking to over 100 industry experts from OEMs, design houses, foundries, heat-treatment and recycling companies and machining companies across the western world backed up by and extensive literature review of over 100 sources.

Legislation in automotive manufacture with respect to CO_2 generation is focussed entirely towards tailpipe emissions and their reduction. There is no consideration for including the CO_2 footprint of the materials used in the manufacture of vehicles. Consequently, the phrase “light- weighting” has become associated with using lower density materials in the belief that this must have reduce the CO_2 footprint of a vehicle. When manufacturing energy is discussed we often hear statements along the lines that “recycled aluminium only requires 5% of the energy primary aluminium”. [1] This ignores the energy from ancillary processes used in the recycling stage to get the material to a condition where it can be reused.

In 2008 Ashby et al. [2] published a research white paper comparing embodied energies in producing components in an automobile across two of the materials life cycle phases – “material” (i.e. extraction and creation of materials for use in a manufacturing phase) and “use”. Their conclusions clearly demonstrate that the energy involved during the “use” phase of a vehicle is much larger than those during the “material” phase of the materials. However, a second section in the paper looks at the sensitivity of substituting a steel bumper weighing 14 kg with and aluminium bumper weighing 10 kg. Their conclusion is that the break-even driving distance in this case is about 200,000 km in favour of the steel component. In other words the vehicle would have to be driven 200,000 km for the so-called light-weighting benefit of substituting the steel with aluminium to start paying back. This is because of the much higher energy content of aluminium alloys or “embodied energy” compared with steel as a result of the huge energy content during both the electrolysis and bauxite conversion stages of the production of aluminium.

Figure 1 shows specific embodied energies as possible design criteria for protecting the environment by Allwood et al. in their paper “Material efficiency: A white paper” [3].

At GIFA 2015 a paper was presented on a similar theme comparing grey cast iron (CI) cylinder blocks with cast aluminium alloy cylinder blocks [4].The results showed that the CO_2 breakeven distance for aluminium cylinder blocks was beyond the useful life of a passenger vehicle. The cylinder block is one of the largest single components in a vehicle and the authors felt it was imperative to investigate further the impact of substitution of denser low environmental impact materials (Fe based) with lower density energy intensive materials (Al alloys) on the energy and CO_2 footprint of a vehicle.



a)

b

Figure 1: a) Young’s modulus and b) tensile strength as a function of embodied energy per cubic metre. Best performing materails are in the top left hand corner i.e. highest value of Young’s modulus or strength for lowest energy. Cast irons outperform Al alloys in both cases using these criteria. (Allwood et al. [3])

Key questions

Three key questions have been raised by the two previously mentioned papers, namely:

- What is the best way of assessing the environmental impact of a vehicle?
- Is light-weighting by reducing material density always the best way of reducing the environmental impact of a vehicle?
- How should design engineers select the correct materials for having the lowest environmental impact through the complete life cycle of the materials used in vehicle manufacture?

Methodology

As well as researching the literature, over 100 experts were contacted from along the automotive supply chain from OEMs, engine design consultancy firms, foundries (both CI and Al), mining companies, primary alloy producers and recycling companies, machining operations, heat treatment and impregnation companies. Hard energy data were obtained from many of these companies and where these were not available the theoretical data were confirmed as accurate by using multiple sources of reference. Embodied energies were calculated using methodologies previously published in the literature by authors such as Brimacombe et al. [5].

The first task was to select a representative engine size to ensure the study was not dealing with niche designs. A study by Trechow in 2011 [6] showed there was a trend that in-line 4 cylinder engines would increase from about 58% of the world-wide market to about 71% by 2016. Discussions with a number of suppliers into the passenger car market drove the study to select a 1.6 L in-line 4 cylinder block as representative of a modern vehicle fleet engine. This was confirmed by follow up conversations with OEM companies. These can be found in both diesel and petrol versions and in both CI and Al Alloy materials.

In order to make the study valid some specific weights were selected for each version of the 4 variations of block. Al alloy engine blocks are often thought to be significantly lighter than cast iron engine blocks. However, due to the fact that cast iron is significantly stronger than cast Al alloys, the difference in weights is not that substantial. So despite the fact that CI is has a density close to 3 times that of cast Al alloys the specific strength and stiffness of the material (i.e. strength/density and elastic modulus/density) alloys thinner wall sections and an overall smaller more compact block to be designed for the same cylinder configuration and often higher power. Based on the results of the comprehensive industry survey, a weight differential of 9 kg was adopted for the 1.6L petrol engine cylinder block and 11 kg for the 1,6L diesel cylinder block. With these differences it is clear that the volume of CI required compared to the Al Alloy is considerably less being in the region of 55% of that of the equivalent Al alloy block. The higher strength and lower volume of material necessary in CI also leads to more compact engines. This in turn leads to an even smaller weight differential in the fully assembled engine, as a result of smaller ancillary components. The authors have based their calculations on an-on-the-road weight differential for the engine of 7 kg and 9 kg for petrol and diesel respectively which was substantiated by a number of design consultancy firms and OEMs.

Another important consideration in the analysis is how much fuel saving can be achieved for every kg saved in mass. Initial considerations based on accepted industry standards have been 6% for every 5 - 10 % in weight saving. However, recent analysis [7] [8] has shown that this may not actually be achievable and that an average of 4.6% is possible but it may actually be as low as 3% - this has a considerable effect on the beak even distances calculated when substituting different materials. This study has adopted 4.6%, as this is the value that has been agreed upon for the 2017 EPA midterm review in the United States [8]. An NRC report from 2010 [9] states that for 1% and 5% weight saving, fuel savings of 0.3% and 3.3% are possible.

Previous work by the authors [10] [11] has investigated the through life energy of cast components looking at the whole life cycle from mining to end of life and it was decided to use the same methodology.

Embodied energies in materials for engine block manufacture

Primary material production

It is essential in the methodology chosen to have a value for the energy used to produce primary materials. Allwood and Cullen [1] suggest that for primary aluminium the figure is of the order of 170 GJ/tonne and for primary iron/steel the figure is about 35 GJ/tonne. Figures found from a variety of websites and publications give values for primary aluminium ranging from 50 to 100 GJ/tonne and for iron of 20 to 40 GJ/tonne. To ensure the authors understood the full life cycle it was decided to go back to basics and calculate figures for the production of both primary aluminium and iron staring from the mining and production of raw materials. These figures would then be used in the correct proportions when used as top-up materials in the casting processes studied. Figure 2 shows the aggregations of energy to produce 1 tonne of liquid aluminium. From the figure it can be seen that for 1 tonne of primary aluminium 98 GJ of energy are required or 265 GJ/m^3.

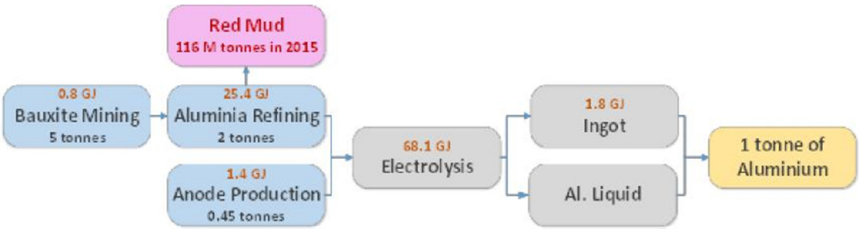


Figure 2: Process flow steps for primary aluminium production with associated energy content to produce 1 tonne of aluminium. Note also that for every tonne of Aluminium there is an associated waste product of 2 tonnes of red mud which has a pH 13 and for which there is no use or value.

A similar calculation can be carried out for the production of pig iron from a blast furnace. Figure 3 shows the equivalent process flow chart and associated energies for iron. The aggregated energy content for 1 tonne of primary iron is calculated to be 17 GJ or 125 GJ/m^3.

Recycled materials in the metal charge

The majority of engine block foundries interviewed use some proportion of recycled material in their charge make-up. When making the calculations for iron a worst case scenario was used for the charge to cover the cases where a higher proportion of pig iron was used than the proportion used in the foundries interviewed for the study all of which used cupola as opposed to induction melting.

The cast iron foundries used a high proportion of steel scrap as a charge material mixed with internal scrap from fettled methoding systems and End Of Life (EOL) CI components. Thus in this study for CI the charge was assume to consist of 91% recycled material which depending upon its provenance (external or internal) has an energy content of 10 GJ/t or 4 GJ/t respectively.

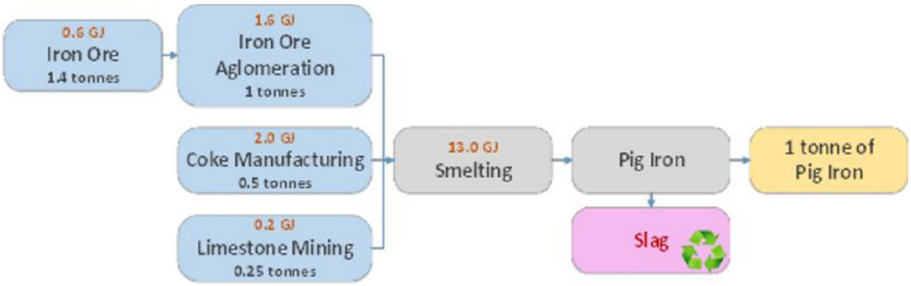


Figure 3: Process flow steps for primary iron production with associated energy content to produce 1 tonne of pig iron. Note that the by-product from the blast furnace know as slag is a glass forming material that is used in aggregate in the construction industry.

The furnace charge that foundries are using for engine block manufacturing comes from 2 different sources – external recycling (new scrap, old scrap, turnings and dross) and in-house recycling. According to foundry practices, the ratio between the two differs. In some cases, (most commonly among aluminium foundries) the metal collected from production processes (new scrap) can be fully reprocessed by external recyclers in a form of closed-loop recycling. Figure 4 illustrates the common processes for the material flow of the recycling model.

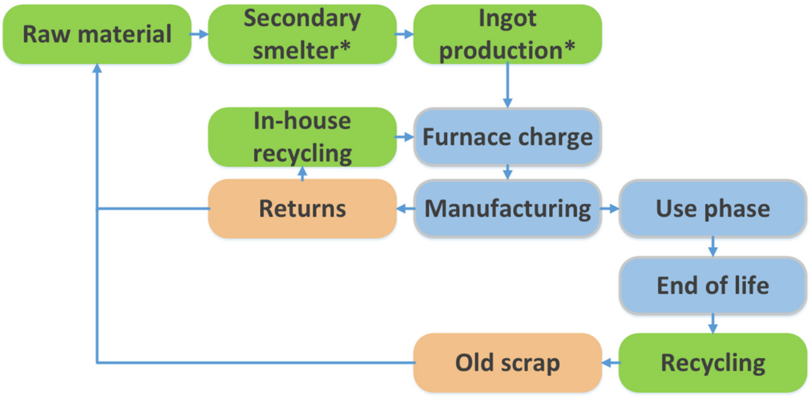


Figure 4: Schematic showing materials recycling routes within the foundries interviewed for the study. Returns are the in-house recycled material from the runners and risers or fettled material. “Old scrap” is material that has been through use as an engine block or other product.
*Secondary smelter and ingot production is only applicable to Al alloys,

It is often stated that recycled Al alloys only require 5% of the energy of primary material to re-process. [1] However, aluminium recycling also involves the processes of shredding, pre-treatment, re-melting and alloying and ingot casting. These additional processes add an estimated 5.7 GJ/t of recycled external scrap to the final processing energies in the foundry.

The Al alloy foundries interviewed for the study varied drastically in their charge materials. Low pressure die-cast foundries (LPDC) used 100% “primary foundry ingot” in A356 alloy and claimed there was no in-house recycling. Low pressure sand (LPS, produced entirely using a core package) used a combination of secondary ingot and in-house recycled A319 alloy (~35%) and recycled foundry ingot to top up for losses thus essentially all the charge material was in some senses recycled. High pressure die casting (HPDC) foundries used a high proportion (27%) of internal scrap added to A380/383 secondary foundry ingot. Calculations assuming the best case scenario for aluminium of infinite recycling gave values of embodied energy of 32, 24 and 25 GJ/t for LPS, LPDC and HPDC respectively. These are different for each process as a result of the recycling rates.

Other materials used in Engine Block Production

Iron is also a raw material required for the manufacture of Al alloy cylinder block as the majority of such blocks have CI liners either cast in or pressed in. These are usually centrifugally cast oversize to allow for machining. Based on the feedback from OEMs in the industry survey, the current study defined that the liners are cast to a wall thickness of 8 mm and pre-machined prior to casting to

5.5 mm then final down to 2 mm after casting and even assuming that 95% of the material is recycled scrap iron then the embodied process energy per set of four liners is 188 MJ or 12 GJ/t.

With respect to alloying and treatment materials, the study included the embodied energy for all alloying elements that comprised more than 1% of the final casting. For the aluminium alloys, this included copper (13.5 GJ/t) [12] and silicon (122 GJ/t) [12], and for cast iron, ferrosilicon is added to enhance the grain structure and metallurgy of the finished component. The energy content to produce 1 tonne of ferrosilicon master alloy is fairly high at just over 30 GJ. However, the addition rate into the iron is such that this contributes 1.6 GJ/t of CI engine blocks.

During standard sand casting, semi-permanent mould casting (cored gravity die-casting) or low pressure sand casting all of which process are used to manufacture cylinder blocks there is energy associated with the mining, preparation, recycling, movement and bonding of the sand. This figure ranges from about 2.3 GJ/t to 5.8 GJ/t of engine blocks and is dependent upon the processes used. On top of that there is also an embodied energy in the recycled sand that is used for cores of moulds. For core sand it was calculated to be 1.8 GJ/t and for green sand 0.2 GJ/t.

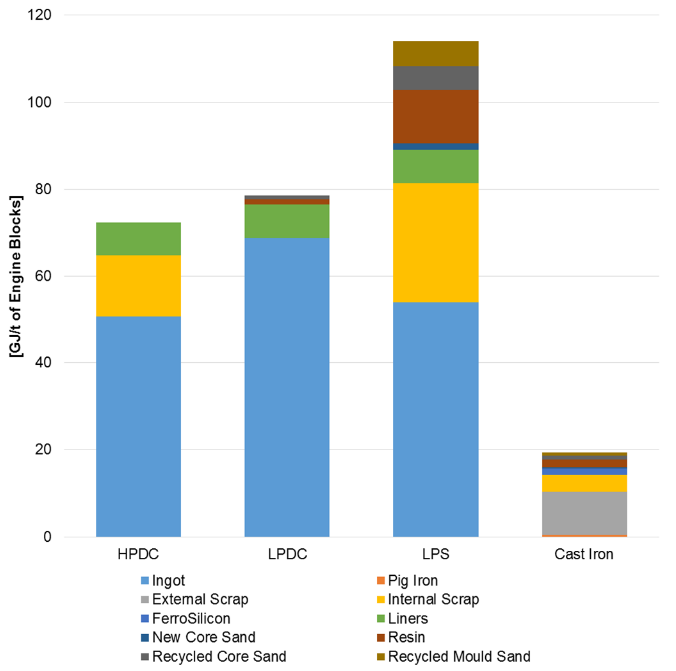


Figure 5: Illustrating the breakdown of material energy embodied per tonne

This study has not included the embodied energies associated with the manufacture of dies for HPDC or LPDC as when amortised across the number of components cast from one die set the amount of energy is trivial. Figure 5 summarises the embodied material energy from all sources.

Process energies in materials for engine block manufacture

Although all the block manufacturing processes were foundry based the CI and three Al alloy processes differed considerably. These processes are summarised in the schematic in figure 6.

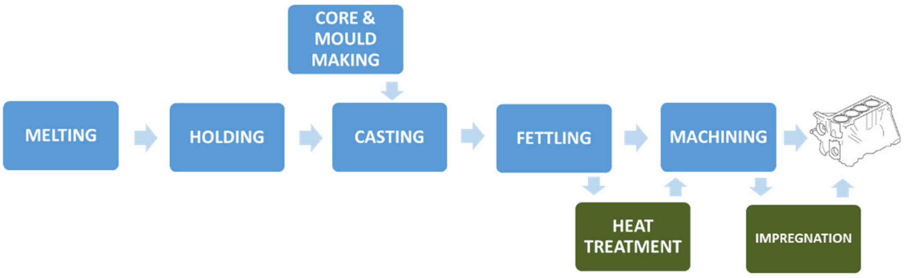


Figure 6: Schematic illustrating the processing steps from raw materials to final cylinder block

Melting, holding, core and mould making and casting

The theoretical amount of energy required to melt 1 tonne of either Al alloy or cast iron and raise it to about 100 ºC superheat is approximately 1 GJ [12] [13]. However, there are not many furnaces that are more than 50% efficient in their performance and the box or mould yield for most foundries is not usually better than 60-65% for Al although with lower material property expectations from high pressure die casting foundries the yields can be pushed to just under 70%. For self-feeding cast iron yields of 75% can be achieved.

Taking these general estimates into consideration one would expect the amount of energy/tonne of castings to be of the order of 2-3 GJ. Figure 7 shows the figures for melting both CI and Al alloys in the foundries interviewed for this study.

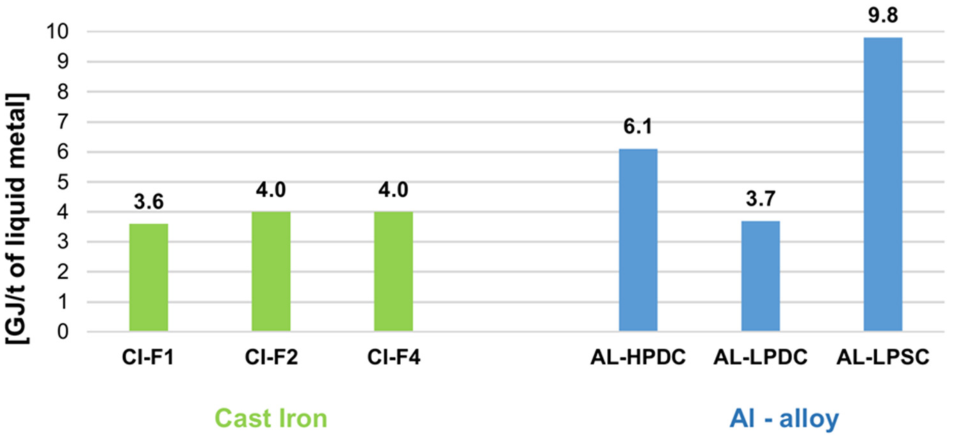


Figure 7: Melting energy recorded in 3 CI and 3 Al alloy foundries showing that the CI foundries all using cupola melting had almost the same energy levels whereas the Al foundries had a range of melting processes and showed much more variation.

For cast iron foundries holding of the liquid metal prior to casting was generally a relatively small aspect of the process whereas for Al alloy foundries holding was a substantial part for the process to allow melt treatments like degassing and cleaning to be carried out. The LPS foundry used an especially long furnace residence time of up to 13 hours to allow iron impurities to settle out. Figure 8 shows the different holding energies recorded by the foundries studied.

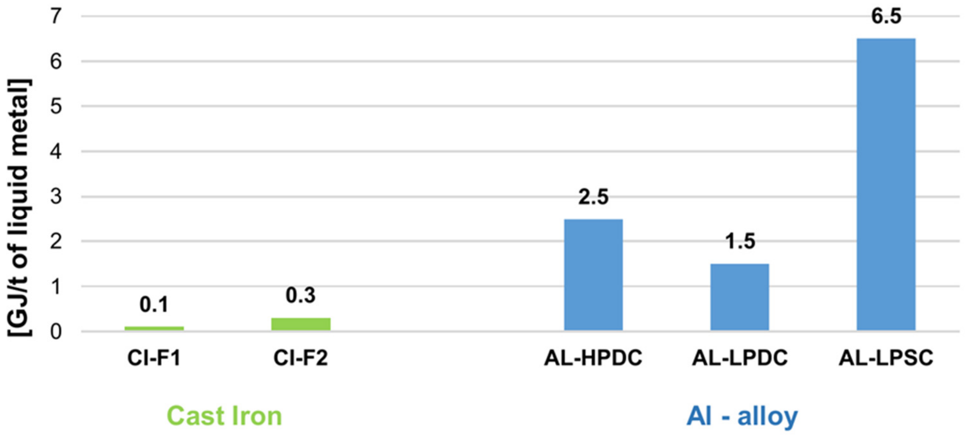


Figure 8: Holding energies for different foundries showing the high energy used for holding in the LPS foundry

In both melting and holding process, from the foundry contacts, an unrecoverable metal loss of 2% was considered for both metals. Although the LPS industry expert suggested that this would not be the case for LPS as the metal is melted under an inert atmosphere of nitrogen thus the loss would be much lower. It was not possible to incorporate the real figure for this case and so a metal loss of 2% was also considered for all Al alloy foundries but it does not significantly change the energy values which are dominated by the very high energy holding and melting processes.

For engine block castings, cores are used to form the complex internal geometry of the block. In aluminium alloy low pressure and gravity and cast iron sand foundries, cores are made from silica sand using the cold box method. In HPDC cores are not used due to the high pressure injection of the metal which would destroy standard sand cores. Core weights recorded were different between the foundries because of different designs. The core weight also varies for the different metals. It was also noted that in the LPDC process the cores were relatively light. However, for LPS this is not the case as because in both LPS and CI process the weight includes the whole core package (cores + mould) (Fig 9). Energies recorded by the foundries for manufacture of cores ranged from 0.5 to 1.5 GJ/t of sand.

The energy during the casting stage of the process consists of moving ladles of molten alloy using cranes or remote lifting devices or in the LPS process the use of an electromagnetic pump. None of the energies involved is large and so for this study they were ignored.

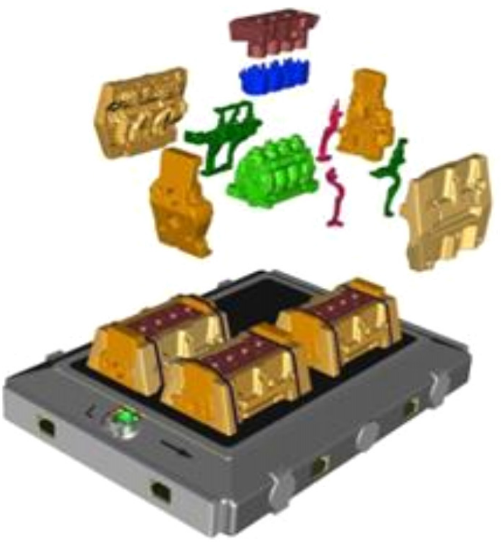


Figure 9: CAD model of typical core and mould package for a 4 on a bed cylinder block method

Post Casting Processes: fettling, heat treatment, machining and impregnation

Post casting process again varied depending upon metal and casting process. One of the most obvious differences between CI and Al was the box or mould yield. The CI did not need feeding the only additional metal required was a running system. This led to an average yield of 76% with only a ± 1% variation. The variation across the Al alloy foundries was much wider ranging from 62% for LPS to 67% for the HPDC. In most cases the fettled material was recycled in house with the exception of the LPDC where it was sent for secondary reprocessing externally. The energy of fettling was also investigated and was a relatively small contributor of about 0.5 GJ/t of finished casting for both alloy systems.

Heat treatment of Al alloys to achieve desired mechanical properties in casting alloys is a standard procedure to increase strength and improve ductility. This usually involves heating the component up to a temperature just below the melting point at about 550 ºC for a time of up to 5 hours depending on the maximum section thickness (solution treatment). This can be referred to a T6 or T7 treatment depending on the aging temperature and time. The component is then quenched in a water, oil or water/polymer bath and the “aged” at a temperature usually close to 200 ºC. It is not usual to post cast heat treat HPDC components by such a process but it is normal practice to apply a stress relieving treatment which does not require heating to the same degree as for full heat treatments. Using both theoretical calculations and interviews with heat treatment companies estimates for T6/T7 treatments are 3.2 – 6.1 GJ/t of finished casting depending on the furnace efficiency. The LPS foundry used a T5 treatment where the casting was heat treated directly after casting without cooling to room temperature. The heat treatment was used to thermally breakdown the mould and cores at the same time and the block was then artificially aged. As the castings are not reheated to solution treat them this used considerably less energy of between 1 and 2 GJ/t. CI does not need a post casting heat treatment process.

Machining was carried out for all cylinder blocks. Surfaces such as cylinder bores, deck face and crankshaft bore are cast with an excess material of up to 3mm that allows later dimensional corrections. A large number of holes must be drilled for oil galleries and bolts. Machining, is the process of removing all this excess material to attain the dimensional accuracy and surface finish according to engine design specifications.

Machining performance and consequently machining energy consumption may vary according to the machining parameters used. The energy can be significantly reduced by arranging for casting feeders to be located on areas which are to be machined. Using a software simulation tool provided by MAG IAS it was possible to estimate the energy consumption for machining using different processes and different materials. This tool estimated that for the Al block with 4 CI liners where 18% of the Al Alloy and 74% of the CI liner are machined away, the energy would be about 2.1 GJ/t whereas for the CI block where 20% of the block is removed, the energy required would be 1.6 GJ/t.

The last post casting process stage is impregnation with a polymer compound to seal the surface breaking porosity. This is usually carried out under a low vacuum process. Most of the energy is in heating water and polymer to 90º C with additional costs being the vacuum pumps, and other ancillary equipment. Impregnation is only applicable to Al alloys and is usually applied to HPDC. Some foundries reported that they impregnated that 100% of all cylinder blocks as a prophylactic measure. In order to give the best case scenario for aluminium it was assumed in the calculations that on average only 30% of Al alloy cylinder blocks are impregnated.

Miscellaneous

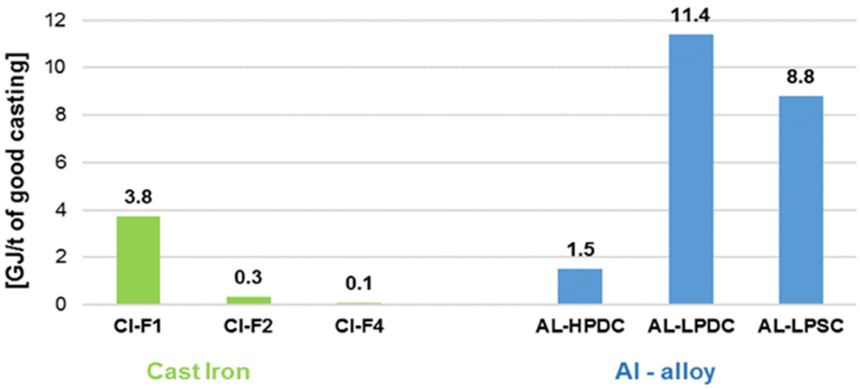


Figure 10: Miscellaneous energy monitoring at the foundries interviewed.

Miscellaneous energy includes energies for the facility operation and other ancillary processes like heating, lighting etc. The energies included in each foundry for the miscellaneous processes vary widely, from 9% to 36%. The reason for such spread is associated with a different classification system in foundry operations. These classification systems can either account only ancillary processes or include manufacturing processes like powder coating or painting of the engine blocks. Figure 10 shows the range of energy classed as miscellaneous.

Scrap

Scrap has an effect on materials efficiency and therefore energy content. Table 1 shows the ranges of scrap in-house and at the customer.

Table 1: Survey result scrap rates at CI and Al Alloy foundries in-house and at the customer

Material	Casting Process	Internal Scrap (%)	External Scrap (%)
Cast Iron	Sand Casting	3	0.5
Al alloy	LPDC	5 – 6.5	0.5
Al alloy	LPS	6 – 6.5	0.5
Al alloy	HPDC	5 – 8.5	0.5

Figure 11 shows the breakdown of process energies in the different foundries.

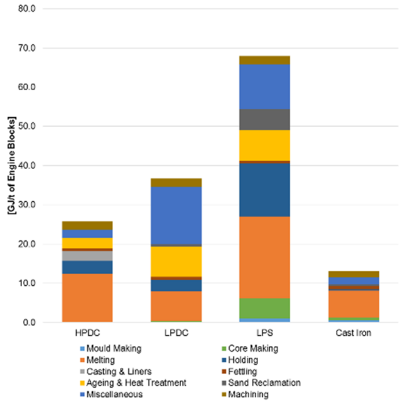


Figure 11: Process energy/tonne of engine blocks made

Materials and Energy flows

Using Sankey diagrams we have represented the energy and materials flows for each of the different types of foundry. These clearly show the largest areas of energy input, recycling loops and material losses. The Sankey tool can be used to show the effect of changing some of the inputs to give the possibility of scenario modelling. Other assumptions used in the analysis are a weight of 200 kg of sand for the cores and mould package for the LPS process, whereas for the CI sand process the core package is 181 kg and an average cylinder liner weight of 1.75 kg.

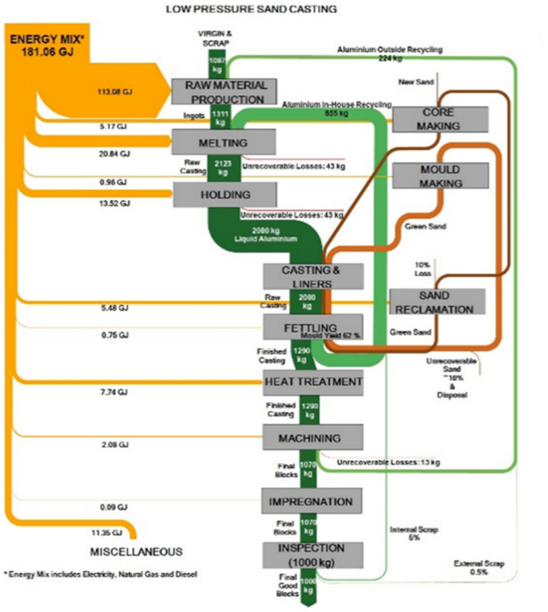


Figure 12: Sankey diagram showing energy and material flows for low pressure sand casting Al cylinder blocks showing that the Operational Materials Efficiency is 46% or Process Energy Burden of 181 GJ/t of good castings

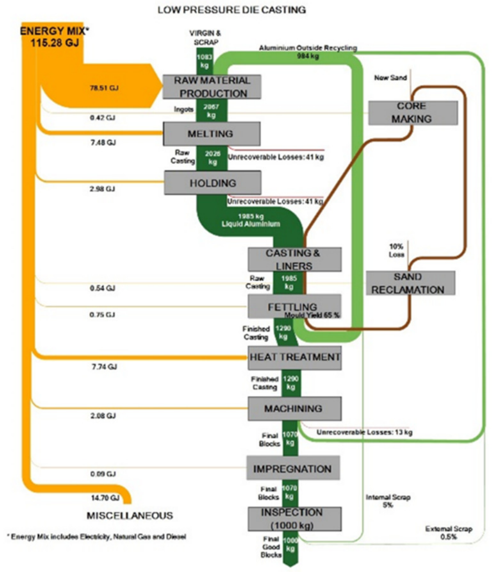


Figure 13: Sankey diagram showing energy and material flows for low pressure die casting of Al cylinder blocks showing that the Operational Materials Efficiency is 48% giving a Process Energy Burden of 115 GJ/t of good castings

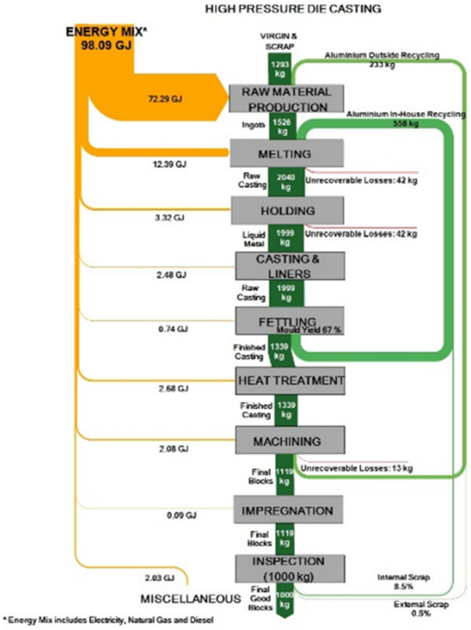


Figure 14: Sankey diagram showing energy and material flows for high pressure die casting of Al cylinder blocks showing that the Operational Materials Efficiency is 48% and the Process Energy Burden is 98 GJ/t of goof good castings

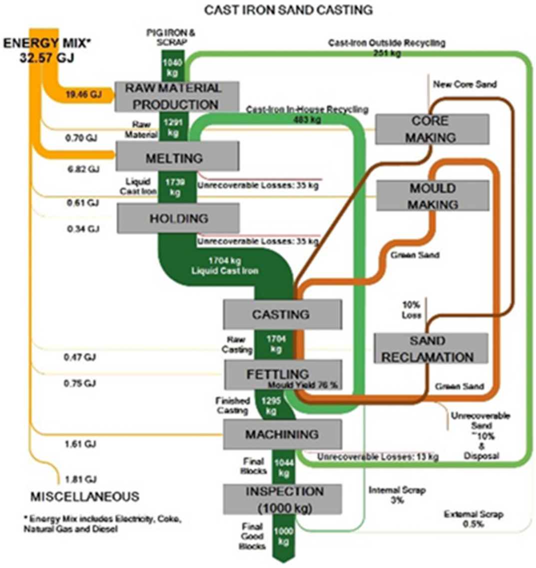


Figure 15: Sankey diagram showing energy and material flows for sand casting of CI cylinder blocks showing the Operational Materials Efficiency is 55% giving a Process Energy Burden of 33 GJ/t of good castings

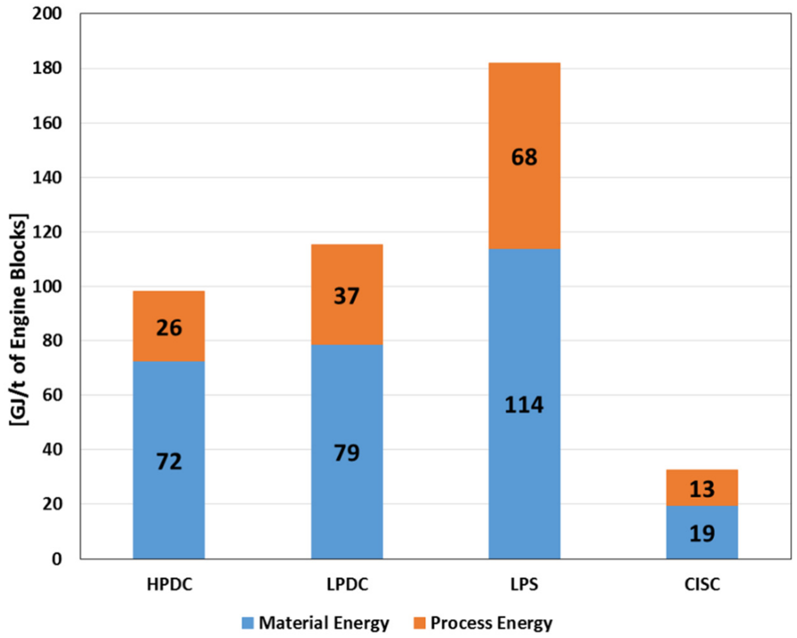
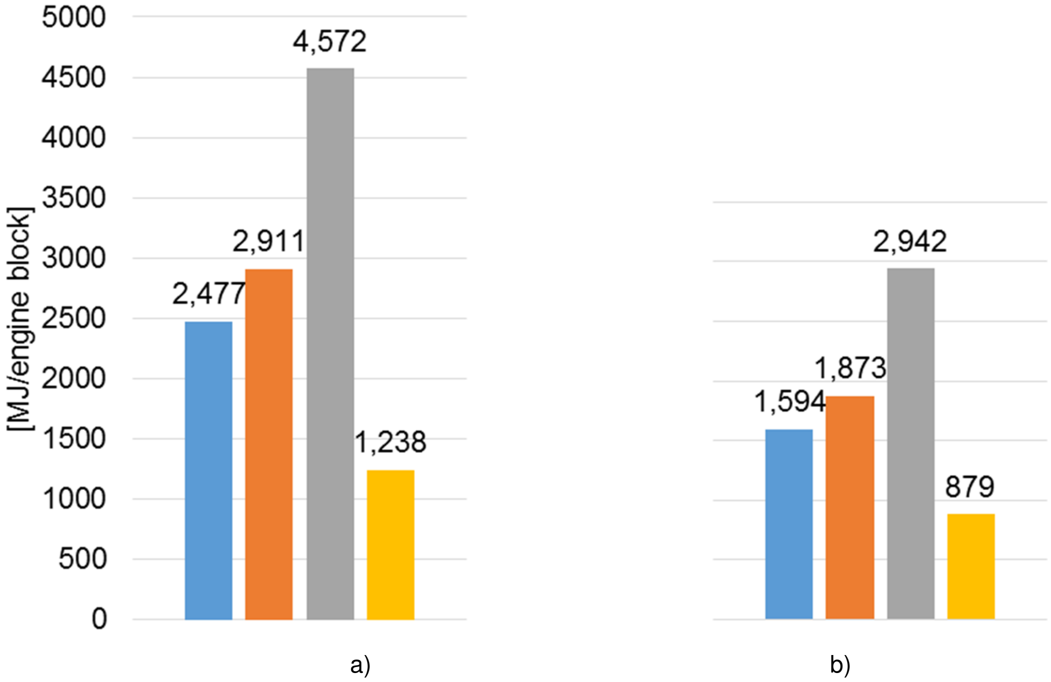


Figure 16: Summary of Process Energy Burden [13] per tonne of good castings for the different casting processes in the study.

Effect of Manufacturing Process Energy Burden (PEB) on Break Even Driving Distance (BED_e)

The previous analysis enables us to compare the energy efficiencies of different manufacturing processes but for the complete sustainability picture we must look at the effect of the PEB on the breakeven distance when substituting materials with lower PEB by materials with high a PEB for the same component. This is achieved by calculating an energy burden per block for each of the processes and each of the fuels. This comparison is shown in figure 17.



a) b)

Figure 17: Comparison of embodied energy per engine block for a) diesel and b) petrol fuels for each of the manufacturing processes.

Taking figure 17 we then calculate the difference in PEB between the lowest (i.e. CI) and the other processes to come up with an energy value that needs to be recovered before the lower weight of the Al alloy engine block starts to give an environmental benefit for the reduced tailpipe emissions. Using the data in table 2 and the differences in PEB between CI and Al Alloy processes (ΔPEB) in equation 1 we can calculate the break-even distance (BED_e) for each process for energy.

$$BED_e = \frac{\Delta PEB}{(\delta F_S \times E_f \times \Delta M\ )} \times 10000 \qquad \textit{Equation 1}$$

Table 2: Values used for break-even calculations based on 4.6% fuel saving for each 10% of weight saving [8]

	Diesel	**Petrol**
Engine weight differential (kg) (ΔM)	9	7
Fuel savings (L/100km/100kg) (δF_s)	0.15	0.20
Energy content (MJ/L) (E_f)	38.6	34.2

These distances are shown in figures 18 and 19.

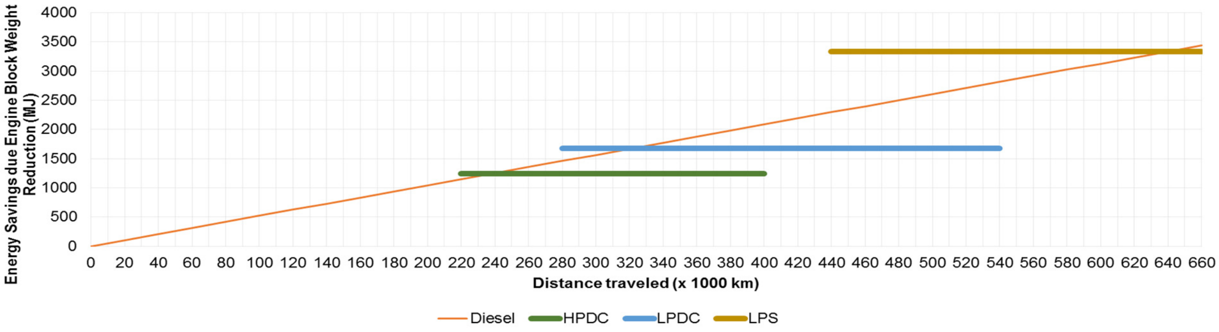


Figure 18: Distance required to drive a diesel powered passenger vehicle with an Aluminium Alloy cylinder block manufactured by different processes compared to an equivalent vehicle with a Cast Iron cylinder block to pay back the energy used in its production. The horizontal length of the line considers the variations of savings achievable.

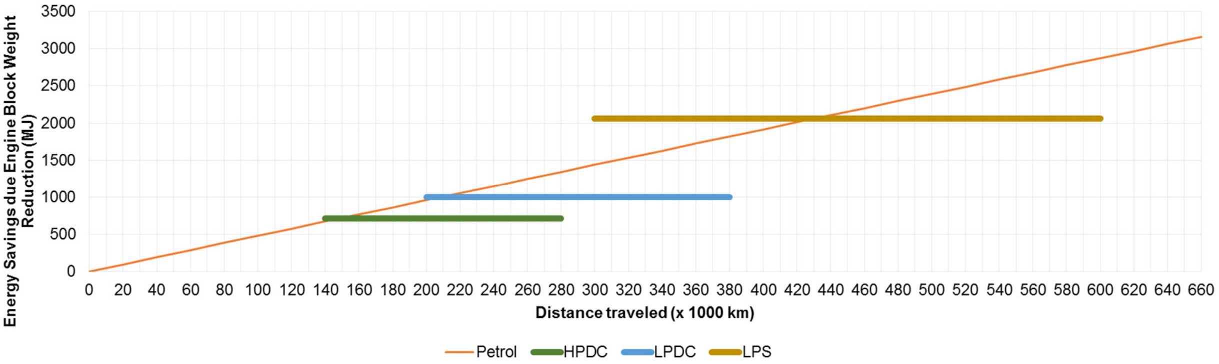


Figure 19: Distance required to drive a petrol powered passenger vehicle with an Aluminium Alloy cylinder block manufactured by different processes compared to an equivalent vehicle with a Cast Iron cylinder block to pay back the energy used in its production. The horizontal length of the line considers the variations of savings achievable.

As mentioned in the introduction a sensitivity analysis was carried out on the effect of changing the level of fuel efficiency for every kg of weight saved the results of this analysis are shown in Table 3. The actual weight reduction is based on the engine weight differences shown in Table 2, expressed as a percent of the total vehicle weight (1,300 kg).

Table 3: Summary of break-even distances for energy (BED$_e$)(km) for different processes and fuels assuming infinite recycling

	HPDC		**LPDC**		**LPS**	
Fuel Efficiency savings (%/5-10% weight reduction)	**Diesel**	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
	0.69% Actual weight reduction	0.54% Actual weight reduction	0.69% Actual weight reduction	0.54% Actual weight reduction	0.69% Actual weight reduction	0.54% Actual weight reduction
6% [14]	214,000	143,000	285,000	192,000	442,000	304,000
4.6% (base case) [8]	271,000	185,000	360,000	250,000	560,000	395,000
3% [9]	407,000	285,000	541,000	385,000	840,000	608,000

One further question arose from the initial assumptions regarding the level of embodied energy taken around each materials cycle. In other words, how many times has the cast iron or aluminium alloy been through the complete loop of being initially primary material and then become a recycled material and how many time has that material been through that loop. Our initial assumption was that as with the published work by Brimacombe [5] the material had been “infinitely” recycled. As we have no way of accurately tracing a materials’ history we do not know where on the asymptotic life cycle to infinite the material actually is. In order to assess what effect this uncertainty has a sensitivity to number of recycling loops was carried out for 5, 10, 15, 20 and infinite loops. The results are dramatic and it is clear that a younger material such as Aluminium which may only have been around the loop a small number of times carried a much higher PEB than if it is assumed it has been infinitely recycled. The base case BED in this case was assumed to be 240,000 km.

The result of these analyses are shown in tables 4 and summary chart figure 20.

Table 4: Effect of number of recycling loops on the break-even distance calculations

Number of recycling cycles	**Breakeven distance (D) (X 1000 km)**					
	HPDC		**LPDC**		**LPS**	
	Diesel	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
5	321	206	414	272	721	487
10	268	170	355	231	669	451
15	254	161	340	220	656	442
20	249	157	333	216	650	438
infinite	240	150	322	210	645	435

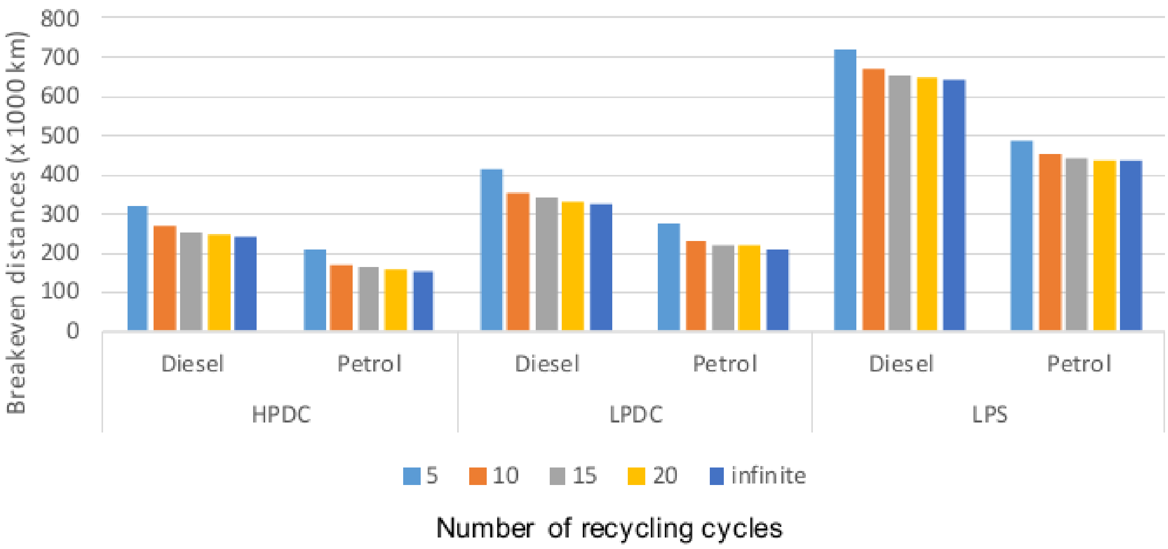


Figure 20: Graphic showing the effect of increasing numbers of recycling loops on the breakeven distance for all three Al alloy casting processes analysed.

Impact of Manufacturing CO_2 emissions on break-even distance

All the calculations so far have focused on the amount of Energy used to manufacture engine blocks followed by a calculation of the energy savings achieved by light-weighting. However, what is actually more important is the impact that the balance of CO_2 produced in the manufacture of the raw materials and subsequent downstream processing has on reduction of CO_2 achieved by light-weighting.

Electricity generation

The CO_2 footprint for Aluminium Alloy production is heavily influence by the location in which the primary aluminium is made as this reflects the source of fuel for producing the energy used during the electrolytic reduction of the aluminium alloy. Table 5 shows the levels of CO_2 created when using different types of electrical generation.

Table 5: Levels of CO_2 created when generating electricity from different sources of energy [15]

Source	t CO_2/TJ	t CO_2/GWhr
Coal	98.5	355
Gasoline	67.7	244
Hydro	2.5	9
Natural Gas	50.4	181
Nuclear	4.2	15
Oil	69.5	250
Propane	59.9	216
Wind	2.8	10

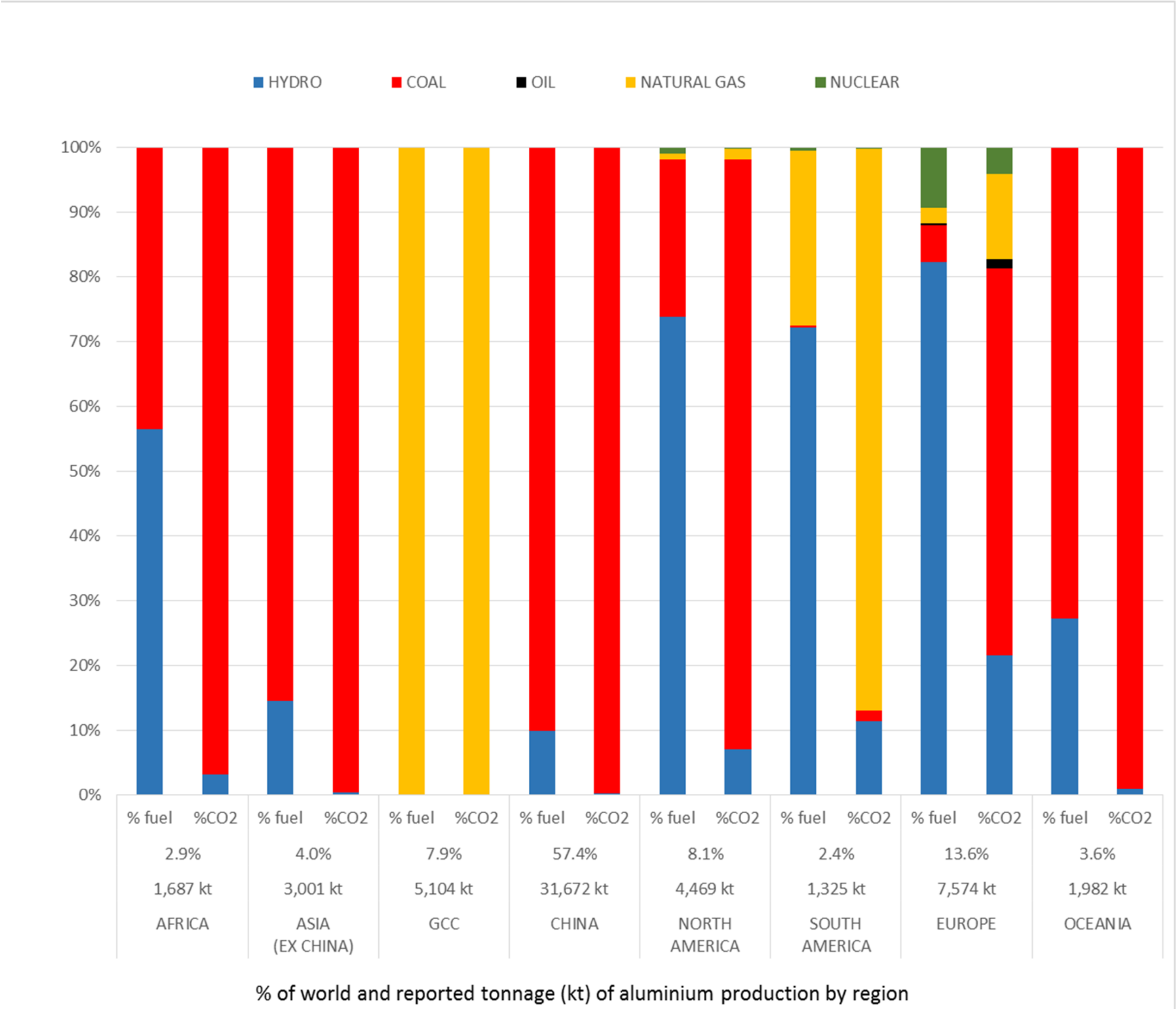
Aluminium production

Table 6 shows the breakdown of primary aluminium production for 2015 from the World Aluminium Organisation.

Table 6: Reported primary aluminium production in 1000s of tonnes for 2015 on a global basis [16]

Africa	**Asia (ex. China)**	**GCC**	**China**	**North America**	**South America**	**West Europe**	**East & Central Europe**	**Oceania**	**ROW**	**TOTAL**
1,687	3,001	5,104	31,672	4,469	1,325	3,745	3,829	1,978	1,080	57,890
2.9%	5.2%	8.8%	54.7%	7.7%	2.3%	6.5%	6.6%	3.4%	1.9%	100.0%

There are very good published data on the sources of electricity used for just the electrolysis of the primary aluminium which is the largest proportion of energy used in primary aluminium production. Figure 21 illustrates the proportion of energy sources used across the world just for the electrolytic production of primary aluminium.



** GCC: Gulf Cooperation Countries: Saudi Arabia, Kuwait, the United Arab, Emirates, Qatar, Bahrain and Oman*

Figure 21: Chart showing the breakdown of energy sources used in the production of electricity for the electrolytic production of primary aluminium in each region. The second bar for each region shows the % CO_2 attributable to each energy source. The horizontal axis also shows the % of reported world production and the tonnage [16]

However although figure 21 appears to show a good proportion of electricity for Al production coming from renewable low CO_2 sources; the proportion in terms of tonnage is 28% (mainly for hydro-electricity) whereas 72% come from fossil-fuel generated electricity (largely coal and natural gas). The amount of CO_2 produced from the electrolysis in the aluminium production for specific energy sources is shown in table 7

Table 7: Global volume of CO_2 produced annually from the production of primary aluminium for different energy sources

Energy source	kt CO_2 pa	%
Hydro	2,086	1.2
Coal	158,418	91.1
Oil	65	0.0
Natural Gas	13,149	7.6
Nuclear	181	0.1
Total	173,899	100.0

In order to represent the total amount of CO_2 burden attributable to the electrolysis stage of the Al production it is important to know the make-up of the energy mix for the aluminium going into the foundries. The research elicited that this is dependent on the manufacturer with some foundries only using primary ingot and others using secondary (recycled ingot) mixed with in-house and external returns. It cannot be assumed that the secondary ingot has no primary aluminium as it is often “sweetened” with primary metal in order to ensure the correct composition. Thus the figures calculated have considered these results to ensure that it represents the cases found in reality. In order to represent the best possible case for aluminium then an infinite recycling loop has been used.

The CO_2 contents calculated have been divided into two aspects coming from the analysis of the energies in the primary study as detailed in Figures 11 and 16 – i.e. materials energy and process energy. Each of the process energies has had an energy source allocated and in some cases a proportion of two different energy sources. For example heat treatment has a proportion of energy from natural gas and some from electricity. Whereas it is assumed that the energy source for machining is predominantly electrical. Where an electrical source of energy is used an average world energy CO_2 footprint is used at 63 kgCO_2/GJ. For the other sources of energy the data is from published data by the Carbon Trust (Table 8) [17].

Table 8: Carbon emission factors [17]:

Fuel	kg C/kWh	kg CO_2/kWh	kg C/MJ	kg CO_2/MJ
Grid electricity Delivered	0.1170	0.4300	0.0325	0.1194
Primary	0.0453	0.1661	0.0126	0.0461
Natural gas	0.0518	0.1900	0.0144	0.0528
Coal	0.0817	0.3000	0.0227	0.0833
Coke	0.1013	0.3730	0.0281	0.1036
Petroleum coke	0.0927	0.3400	0.0258	0.0944
Gas/diesel oil	0.0680	0.2500	0.0189	0.0694
Heavy fuel oil	0.0709	0.2600	0.0197	0.0722
Petrol	0.0655	0.2400	0.0182	0.0667
LPG	0.0573	0.2140	0.0159	0.0594
Jet kerosene	0.0655	0.2400	0.0182	0.0667
Ethane	0.0545	0.2000	0.0151	0.0556
Naphtha	0.0709	0.2600	0.0197	0.0722
Refinery gas	0.0545	0.2000	0.0151	0.0556

The factors given above are taken from Annex A of UKETS (01)05 (Guidelines for the measurement and reporting of emissions in the UK Emissions Trading Scheme).These figures are consistent with the National Air Emission Inventory and with the carbon factors given in the generic PP3.02.

From these data, Figure 22 and Table 9 were developed showing the ratio of CO_2 from the raw materials production, from mining to casting including secondary processing in the relevant proportions and from the post casting processes.

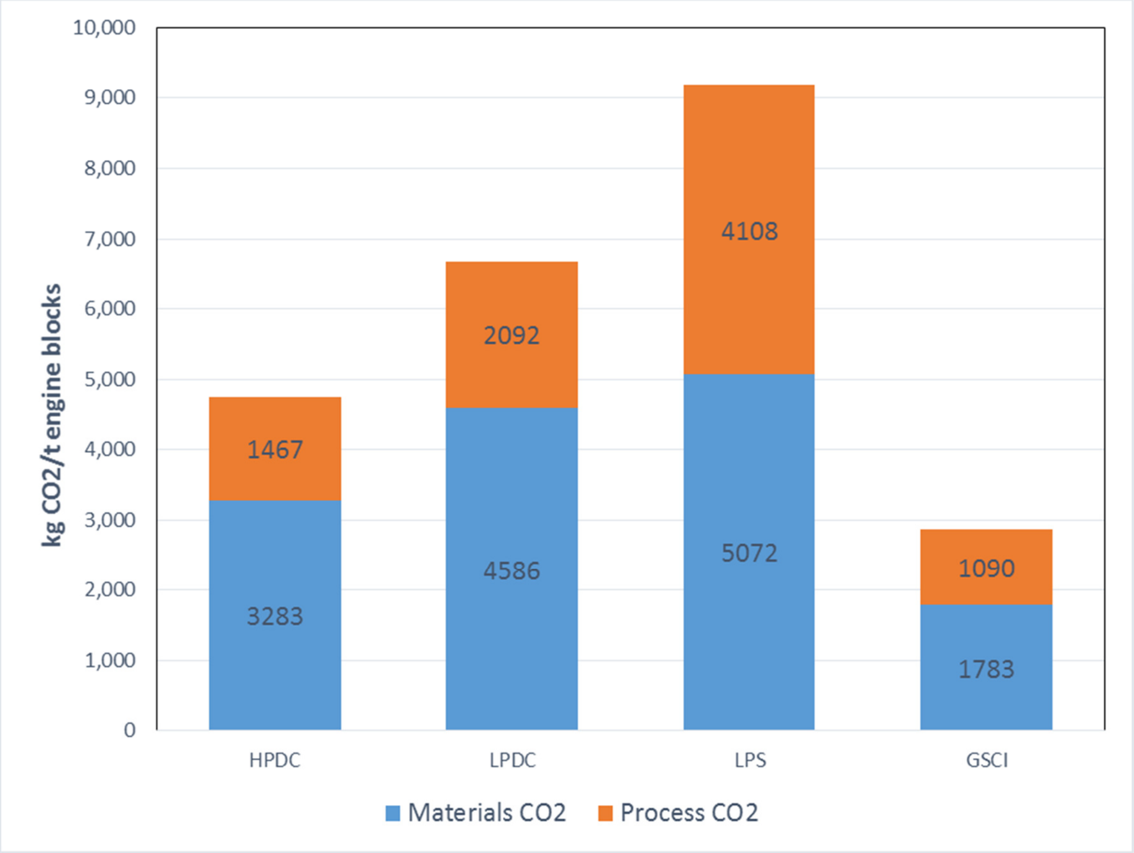


Figure 22: Summary of CO_2 burden per tonne of good castings for the different casting processes in the study.

Table 9: CO_2 emissions associated with casting production of cylinder blocks

Process	**Energy/tonne of blocks cast**	**Raw materials production**	**Casting & ancillary processes**	**Total CO_2 emissions**	**Difference in CO_2 between Al and CI ΔC**	**Ancillary Processes**
	(GJ/t)	**(kg CO_2/t)**	**(kg CO_2/t)**	**(kg CO_2/t)**	**(kg CO_2/t)**	**%**
HPDC	98.2	3283	1467	4750	1876	31%
LPDC	115.4	4586	2092	6678	3805	31%
LPS	181.1	5072	4108	9780	6907	45%
GSCI	32.6	1783	1090	2873	-	38%

Break-even distances (BED_c) for CO_2 emissions

Using the same methodology as was used earlier to calculate the BED for the energy of manufacture, a similar calculation has been carried out for each process to assess the distance it is necessary to drive a vehicle with an aluminium alloy block to make up for the differences in CO_2 generated in during its manufacture. Equation 2 mirrors Equation 1 but is for the CO_2

$$BED_c = \frac{\Delta C_b}{\delta F_s \times E_f \times C_f \times \Delta M} \times 10000 \qquad \textit{Equation 2}$$

Figures 23 and 24 show the BED_c similarly to the BED_e showing the range expected depending of the case used as detailed in Table 11.

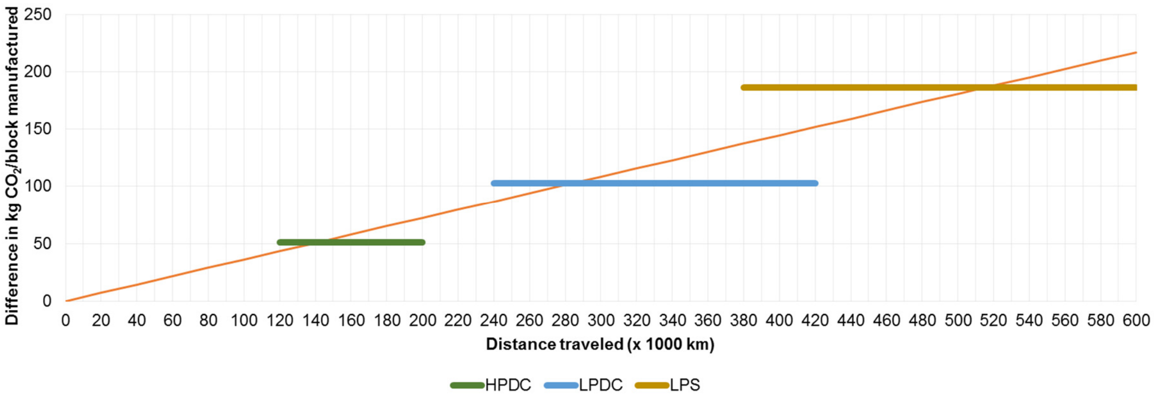


Figure 23: Distance required to drive a diesel powered passenger vehicle with an Aluminium Alloy cylinder block manufactured by different processes compared to an equivalent vehicle with a Cast Iron cylinder block to pay back the CO_2 used in its production. The horizontal length of the line considers the variations of savings achievable.

Using the same rationale as for the calculations for the energy BED_e for different fuel savings and for different weight savings (Table 3) the same calculations have been carried out for CO_2 BED_c and are shown in Table 11. Again, the breakeven distances are based on the engine weight reduction values shown in table 2 and the total vehicle weight of 1,300 kg.

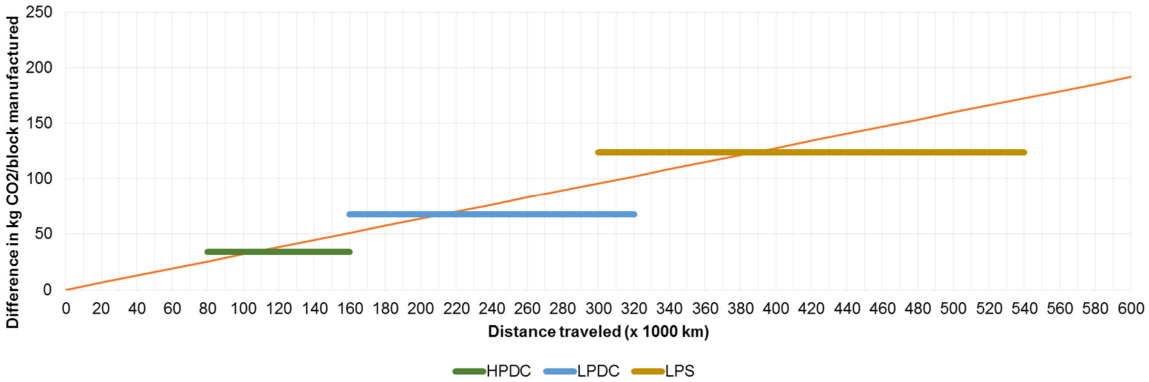


Figure 24: Distance required to drive a petrol powered passenger vehicle with an Aluminium Alloy cylinder block manufactured by different processes compared to an equivalent vehicle with a Cast Iron cylinder block to pay back the CO_2 used in its production. The horizontal length of the line considers the variations of savings achievable.

Table 11 Summary of break-even distances for CO_2 (BEDc)(km) for different processes and fuels assuming infinite recycling

Fuel Efficiency savings (%/5-10% weight reduction)	**HPDC**		**LPDC**		**LPS**	
	Diesel	**Petrol**	**Diesel**	**Petrol**	**Diesel**	**Petrol**
	0.69% Actual weight reduction	0.54% Actual weight reduction	0.69% Actual weight reduction	0.54% Actual weight reduction	0.69% Actual weight reduction	0.54% Actual weight reduction
6% [14]	111,000	81,000	224,000	165,000	371,000	274,000
4.6% (base case) [8]	140,000	106,000	284,000	215,000	471,000	356,000
3% [9]	210,000	163,000	426,000	330,000	706,000	547,000

Conclusions

Analysing the effect on the environment of substitution on materials in passenger vehicles is highly complex and affected by many assumptions that must be considered and decisions taken. The present study is based on a comprehensive survey of the iron and aluminium supply industries to minimise the impact of such assumptions on the results.

It is clear that tail-pipe emissions do not adequately asses the effect on the environment when making decisions about light-weighting and fuel savings and this was clearly demonstrated by Ashby et al 2008 [2].

From this research conducted from analysing over one hundred primary sources and given the parameters selected i.e. a 1.6 L in-line 4 cylinder block, substituting cast iron products with aluminium alloy components does not create more environmentally friendly vehicles when considering the total energy of manufacturing and actual fuel savings achieved. In fact, in order to recover the differences in the energy of manufacture throughout the whole materials cycle it is necessary to drive a car substituted with an Al alloy cylinder block a minimum of between 143,000 km and 840,000 km depending on the precise method of manufacture and the way in which the vehicle is driven. This is a direct result of the high primary energy content in aluminium alloys and the very small weight saving achieved by the substitution being less than 1% of the total mass of the car.

The most likely fuel savings based on reports from both the US National Research Council and National Academy of Sciences [8, 9], shown as the base case with fuel saving of 4.6% for each 100 km of weight saved and 100 km driven, give break even distances for energy (BED_e) from using Cast Iron of between 185,000 and 560,000 km and for CO_2 (BED_c) of between 106,000 and 471,000 km depending on the manufacturing process and fuel.

For some manufacturing scenarios, the break-even distances calculated from the results of this study are close to the expected life of a vehicle. However, for most of the manufacturing scenarios, the break-even distances are well beyond the vehicle life.

Other environmental issues are essential to consider when using Al alloy substitution, namely the recyclability of the alloy and the effect on the environment of the production of primary aluminium not just in energy content but also waste products such as the so called “red mud”.

Current legislation does not adequately represent the full energy content of cars or indeed many manufactured products and it behoves legislators and politicians to take serious considerations of these aspects if we are to not make badly justified decisions regarding the use of materials in many applications – not just in transportation.

Acknowledgements

The authors would like to acknowledge the supreme effort of the masters students who carried out the research work namely; Emma Caicedo-Portillo, Micael Teixeira Goncalves, Yan Huaizhong, Noemi Macura, Spyridon Kokolis-Karolidis, Joseph Tucker and Yanni Yang.

References

[1] J. M. Allwood and J. M. Cullen, Sustainable materails with both eyes open, UIT Cambridge, 2012.

[2] M. Ashby, N. Ball and N. Bream, “The CES EduPack Eco Audit Tool – A White Paper,” Granta Design, Cambridge, 2008.

[3] J. M. Allwood, M. F. Ashby, T. G. Gutowski and E. Worrell, “Material efficiency: A White Paper,” *Resources, Conservation and Recycling,* vol. 55, pp. 362-381, 2011.

[4] A. Sobota and W. Gortz, “Energy Balance and CO2Emissions Study for the Total Life Cycle of Cylinder Blocks Produced from Aluminium and Cast Iron,” in *GIFA*, Dusseldorf, 2015.

[5] L. Brimacombe, N. Coleman and C. Honess, “Recycling, reuse and the sustainability of steel,” *Millenium Steel,* pp. 31 -36, 2005.

[6] P. Trechow, VDI Nachrichten, 2011.

[7] S. Ahmed, “Cramming for Midterms,” *Automotive News,* 18 April 2016.

[8] Board on Energy and Environmental Systems, “Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles,” The National Academy of Sciences, 2015.

[9] Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, National Research Council, “Assessment of Technologies for Improving Light,” National Academies Press, Washington, 2010.

[10] B. Zeng, K. Salonitis and M. R. Jolly, “Comparison of the environmental impact of the CRIMSON process with normal sand casting process,” in *11th International Conference on Manufacturing Research: Advances in MAnufacturing Technology* , 2013.

[11] B. Zeng, K. Salonitis and M. R. Jolly, “Investigating the energy consumption of casting process by multiple life cycle method,” in *International conference on Sustainable Design and Manufacturing*, Cardiff, 2014.

[12] Granta Design, “CES Edupack Database,” Granta Design, Cambridge, 2016.

[13] M. R. Jolly, X. Dai and B. Zeng, “Energy Saving in the Foundry Industry by using the CRIMSON Single Shot up-Casting Process,” in *World Foundry Congress*, Saltillo, Mexico, 2012.

[14] A. Casadei and R. Broda, “RD.07/71602.2: Impact of vehicle weight reduction on fuel economy for various vehicle architectures,” Ricardo, 2007.

[15] “Industrial Efficienct Technology Database,” The Institute for Industrial Productivity, [Online]. Available: http://ietd.iipnetwork.org/. [Accessed 26 August 2016].

[16] International Aluminium Institute, [Online]. Available: http://www.world-aluminium.org/statistics/#data. [Accessed 3 11 2016].

[17] Carbon Trust, “Energy and carbon conversions,” HMSO (DEFRA), London, 2006.

[18] M. R. Jolly, “Chapter 18: Castings,” in *Comprehensive Structural Integrity*, vol. 1, R. O. Ritchie, B. L. Karihaloo and I. Milne, Eds., Amsterdam, Elsevier, 2003, p. 368¬464.